

Search for Beyond the Standard Model Higgs Bosons at the Tevatron

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Results are presented [1] for recent beyond the Standard Model Higgs searches using between 1 and 4.2 fb^{-1} of data from Run II at the Tevatron. No significant excess is observed in any of the studied channels so limits at 95% confidence level are presented.

1 Introduction

The search for Higgs bosons is one of the main challenges for particle physics and is a high priority for the upgraded CDF and DØ detectors at Run II of the Tevatron. There are many alternative Higgs models beyond the SM, including Supersymmetry (SUSY) [2] and Fermiophobic Higgs [3], which can actively be probed at the Tevatron, and in the absence of an excess excluded. The latest limits for several SUSY searches are presented in Section 2 and for the Fermiophobic Higgs searches in Section 3. More information is available on all the searches outlined here, along with the latest results, from the public pages of CDF and DØ [4, 5].

2 Minimal Supersymmetric Standard Model Higgs Searches

The Minimal Supersymmetric extension of the SM (MSSM) [2] introduces two Higgs doublets which results in five physical Higgs bosons after electroweak symmetry breaking. Three of which are neutral, the CP-odd scalar, A , and the CP-even scalars, h and H (of which h is the lighter and SM like), and two of which are charged, H^\pm .

At tree level only two free parameters are needed for all couplings and masses to be calculated. These are chosen as the mass of the CP-odd scalar (m_A) and $\tan\beta$, the ratio of the two vacuum expectation values of the Higgs doublets.

The Higgs production cross section in the MSSM is proportional to the square of $\tan\beta$. Large values of $\tan\beta$ thus result in significantly increased production cross sections compared to the SM. Moreover, one of the CP-even scalars and the CP-odd scalar are degenerate in mass, leading to a further approximate doubling of the cross section.

The main production mechanisms for the neutral Higgs bosons are the $gg, b\bar{b} \rightarrow \phi$ and $gg, q\bar{q} \rightarrow \phi + b\bar{b}$ processes, where $\phi = h, H, A$. The branching ratio of $\phi \rightarrow b\bar{b}$ is around 90% and $\phi \rightarrow \tau^+\tau^-$ is around 10%. This results in three channels of interest: $\phi \rightarrow \tau^+\tau^-$, $\phi b \rightarrow b\bar{b}b$ and $\phi b \rightarrow \tau^+\tau^-b$. The overall experimental sensitivity of the three channels is similar due to the lower background from the more unique signature of the τ decays.

2.1 Higgs $\rightarrow \tau^+\tau^-$

* On behalf of the CDF and DØ Collaborations.

DØ's latest search is for the $\tau_\mu\tau_{had}$ final state using 1.2 fb^{-1} of Run IIb data, where τ_{had} refers to a hadronic decay and τ_μ refers to a leptonic decay of a τ . This result is combined with the published Run IIa 1 fb^{-1} result for the $\tau_\mu\tau_e$, $\tau_\mu\tau_{had}$ and $\tau_e\tau_{had}$ channels [6]. Events are required to have an isolated μ , with $p_T > 10 \text{ GeV}$ and $|\eta| < 2.0$, separated from an opposite signed τ_{had} by $\Delta R > 0.5$. Hadronic tau candidates are identified by the standard DØ artificial neural networks designed to distinguish τ_{had} from QCD jets. To remove most of the W+jets background, events are required to have transverse mass, defined as $M_T = \sqrt{2p_T^\mu E_T(1 - \cos\Delta\phi)}$, less than 40 GeV. The dominant backgrounds are $Z/\gamma \rightarrow \tau\tau$ which is simulated using PYTHIA [10] and QCD and W+jets backgrounds which are modeled using data.

CDF has conducted searches for the $\tau_\mu\tau_e$, $\tau_\mu\tau_{had}$ and $\tau_e\tau_{had}$ final states using 1.8 fb^{-1} of data. The $\tau_\mu\tau_{had}$ ($\tau_e\tau_{had}$) events are selected by requiring an isolated μ (e), with p_T (E_T) $> 10 \text{ GeV}$ and an oppositely charged τ_{had} . Hadronic tau candidates are reconstructed using a variable size isolation cone. Events in the the $\tau_\mu\tau_e$ channel are selected by requiring a μ with $p_T > 10 \text{ GeV}$ and an e with $E_T > 6 \text{ GeV}$ or vice-versa. To remove most of the W+jets background a cut is placed on the relative direction of the visible τ decay products and the missing E_T . The QCD and W+jets contribution is modeled using data and the $Z/\gamma \rightarrow \tau\tau$ using PYTHIA.

Limits are set using the visible mass distribution (m_{vis}), which is the invariant mass of the visible tau products and the missing E_T . The 95% confidence level (CL) limit is shown in Fig. 1 for the CDF search interpreted in a standard MSSM scenario [7]. The DØ search has a similar sensitivity.

2.2 Higgs + $b \rightarrow b\bar{b}$

The signature of this channel is at least 3 b jets in the final state and consequently the background is dominated by QCD multijet heavy flavour. DØ and CDF have both conducted a search in this channel using 2.6 fb^{-1} and 1.9 fb^{-1} of data respectively.

DØ requires between 3 and 5 jets with $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$. Three of the jets must be tagged as a b jet using the standard DØ neural network b -tagging algorithm [9]. The analysis is split into exclusive 3, 4 and 5-jet channels to increase the sensitivity. A likelihood is trained in each channel to differentiate the QCD multijet background from signal. A cut is placed on the likelihood of between 0.25 and 0.6 depending on the mass point. In the absence of an excess, the dijet invariant mass distribution in the high likelihood region is used to set limits. The

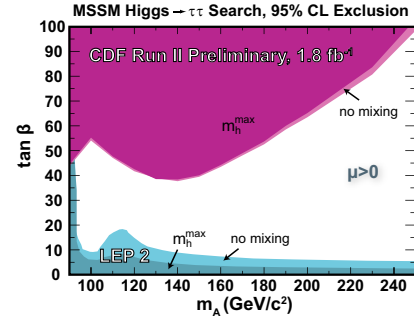


Figure 1: The 95% exclusion for $\mu > 0$ for the no-mixing and m_h^{max} scenarios. The shaded blue area is the region excluded by LEP [8].

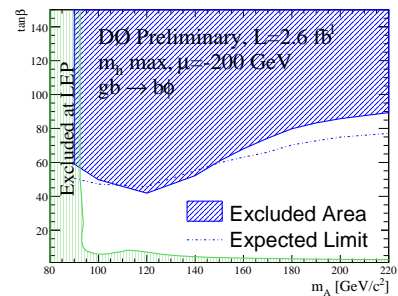


Figure 2: The 95% exclusion for the $\mu < 0$, m_h^{max} scenario. The green area is the region excluded by LEP.

simulation of signal and background is performed with PYTHIA or ALPGEN [11] interfaced with PYTHIA and passed through the detailed detector simulation. QCD multijet production is estimated from data.

The CDF search requires exactly 3 jets, with $p_T > 20$ GeV and $|\eta| < 2.0$. All three jets must be tagged by the standard CDF secondary vertex algorithm. Signal and background events are both simulated using PYTHIA and the QCD multijet events are modeled from data.

Both analyses set upper limits on the Higgs production cross-section times branching ratio using the dijet mass as the discriminating variable. Figure 2 shows the $D\bar{O}$ limit.

2.3 Higgs + $b \rightarrow \tau^+\tau^-b$

$D\bar{O}$ has performed a search using 1.2 fb^{-1} of Run IIb data for the $\tau_\mu\tau_{had}$ decays of the taus. Events are required to have an isolated μ separated from an opposite sign τ_{had} candidate and a jet b tagged using the neural network b -tagging algorithm. The μ must have $p_T > 12$ GeV, $|\eta| < 2.0$ and be matched to a central track. Hadronic taus are identified using the standard $D\bar{O}$ artificial neural networks (ANN). The dominant backgrounds are $t\bar{t}$ and QCD jets. The QCD multijet background is estimated from data and the $t\bar{t}$ background is modeled using ALPGEN interfaced with PYTHIA. $t\bar{t}$ events are removed using an ANN based upon kinematic variables. QCD multijets are removed using an unbinned log-likelihood ratio. The 2D QCD likelihood output versus $t\bar{t}$ ANN output distribution is used for limit setting. Figure 3 shows the resulting 95% CL exclusion in the $\tan\beta - m_A$ plane.

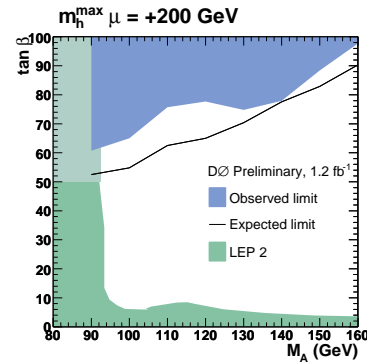


Figure 3: Limits on $\tan\beta$ versus M_A for the $\mu > 0$, m_h^{max} scenario.

2.4 Charged Higgs

CDF has carried out a search for H^+ using 2.2 fb^{-1} of data in the low $\tan\beta$ region which is dominated by the decay $H^+ \rightarrow c\bar{s}$. The search was conducted in the lepton+jets $t\bar{t}$ channels. Events were required to have one isolated lepton e (or μ) with E_T (or p_T) > 20 GeV, missing $E_T > 20$ GeV and 4 jets, with $E_T > 20$ GeV and $|\eta| < 2.0$, two of which must be tagged as b-jets by the secondary vertex tagging algorithm. The two non b-tagged jets are assumed to be from the W^+ or H^+ decay. Mass templates for H^+ and W^+ are fit to the data dijet mass distribution to extract upper limits on the branching ratio of $t \rightarrow H^+b$. The dominant background is $t\bar{t}$ which is modeled using PYTHIA MC. Upper limits on the $BR(t \rightarrow H^+b)$ of $0.3 - 0.1$ have been set dependent on the H^+ mass.

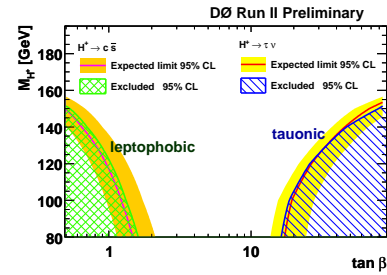


Figure 4: $D\bar{O}$ limits on the charged Higgs mass as a function of $\tan\beta$.

DØ carried out a search using 1 fb^{-1} of data. The search was conducted in the lepton+jets (e +jets, μ +jets) and dilepton (ee , $\mu\mu$, $e\mu$, $\mu\tau$, $e\tau$) decay channels. Searches were conducted in the $\tan\beta < 1$ region where the tauonic decay, $H^+ \rightarrow \tau\nu$, dominates and in the $\tan\beta > 1$ region where the leptophobic decay, $H^+ \rightarrow c\bar{s}$, dominates. In the leptophobic decay a suppression of the expected $t\bar{t}$ yield would indicate the presence of the H^+ decay in all channels. In the tauonic decay a deficit in all channels except for the lepton+jets channel would indicate the presence of the H^+ . The signal was modelled using PYTHIA and $t\bar{t}$ production modelled using ALPGEN interfaced with PYTHIA. The 95% CL exclusion limits for both DØ searches are shown in Fig. 4.

2.5 Next-to-MSSM

In the next-to-MSSM (nMSSM) [12] the branching ratio of $\text{Higgs} \rightarrow b\bar{b}$ is greatly reduced. Instead the Higgs predominantly decays to a pair of lighter neutral pseudoscalar Higgs bosons, a . The nMSSM scheme is interesting as it allows the LEP limit on the h boson to be naturally lowered to the general Higgs search limit from LEP of $M_h > 82 \text{ GeV}$ [13]. DØ conducted two nMSSM searches, firstly for the case where $2M_\mu < M_a \lesssim 3M_\pi$ where a dominantly decays to two muons. Secondly, in the case of $2M_\tau < M_a \lesssim 2M_b$ where a predominantly decays to two taus.

In the case of $a \rightarrow \mu\mu$ the event signature is two pairs of collinear muons. Due to the extreme collinearity of the μ pair, and the limited resolution of the μ system, only one μ is likely to be reconstructed. The event selection therefore only requires two muons, which must be separated by $\Delta R(\mu, \mu) > 1$. Each μ must have a companion track with $p_T > 4 \text{ GeV}$ within $\Delta R < 0.4$. The main backgrounds are QCD jets and $Z/\gamma \rightarrow \mu\mu + \text{jets}$. The QCD jets are modeled using a data control region and the Z/γ background is modeled using PYTHIA. Limits are set by fitting a gaussian to the companion track-muon invariant mass peak and counting events in a 2σ 2D window around the gaussian fit means for both companion track-muon pairs. Limits are set using a Bayesian method and are shown in Table 1.

In the case of $a \rightarrow \tau\tau$, due to the lack of an observed resonance and the difficulty of triggering on a four tau signature, one of the a bosons is required to decay to two muons. The event selection requires two isolated muons with $p_T > 10 \text{ GeV}$ and $\Delta R(\mu, \mu) < 0.5$ with dimuon invariant mass, $M(\mu, \mu) > 20 \text{ GeV}$. Due to the difficulty of reconstructing two overlapping tau decays no explicit tau reconstruction is attempted and instead missing $E_T > 25 \text{ GeV}$ is required opposite the μ pair. The QCD background is modeled using a data control region and other electroweak and top back-

M_a	Exp. (fb)	Obs. (fb)
0.2143	12.0	12.0
0.3	10.5	10.5
0.5	9.5	9.5
1	9.3	9.3
3	9.5	9.5

Table 1: Expected and observed limits on $\sigma(p\bar{p} \rightarrow h + X) \rightarrow aa \rightarrow \mu\mu$ assuming $M_h = 100 \text{ GeV}$.

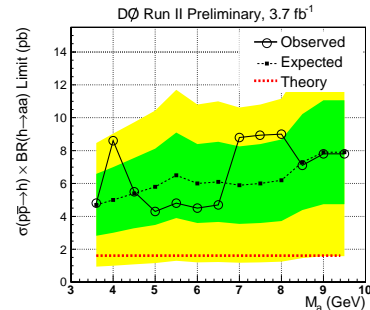


Figure 5: Limits for $\sigma(p\bar{p} \rightarrow h + X) \rightarrow aa$, assuming $M_h = 100 \text{ GeV}$. The SM cross section is shown as the thick dashed band.

grounds are modeled using PYTHIA. Limits are set by fitting a gaussian to the dimuon invariant mass peak and counting events in the $\pm 2\sigma$ mass window. The limits are shown in Fig. 5.

3 Fermiophobic Higgs

The Standard Model Higgs branching ratio to decay to a pair of photons is small. There are however several models where the decay of the Higgs boson to fermions is suppressed. In these models the decay of the Higgs boson to photons is greatly enhanced. Both DØ and CDF have carried out searches for the Fermiophobic Higgs boson using 4.2 and 3.0 fb⁻¹ respectively.

DØ requires two photon candidates with $|\eta| < 1.1$ and $p_T > 20$ GeV. Jets misidentified as photons are rejected by using an artificial neural network. Electrons are suppressed by requiring that the photon candidates are not matched to activity in the tracking detectors. The three main background sources are estimated separately: the jet and diphoton backgrounds are estimated from data and the Drell-Yen contribution is estimated using Pythia.

CDF's search also requires two photons with $p_T > 15$ GeV. However, only one is required in the central region, $|\eta| < 1.05$, whilst the second photon can also be in the end region $1.2 < |\eta| < 2.8$. This looser photon requirement approximately doubles the acceptance. In addition a cut is placed on the transverse momentum of the two photons, $p_T^{\gamma\gamma} > 75$ GeV which was found to maximise sensitivity. The background is estimated using a purely data-based approach.

Upper limits are set on the Higgs production cross section times branching ratio using the diphoton mass as the discriminating variable. The 95% CL are shown in Fig. 6 for the CDF search. Lower limits were set on the mass of a Fermiophobic Higgs, $M_{hf} > 102.5$ GeV by DØ and $M_{hf} > 106$ GeV by CDF, both searches provide access to the $M_{hf} > 125$ GeV region which was inaccessible at LEP.

4 Conclusions

CDF and DØ have a wide variety of active beyond the Standard Model Higgs searches, presented here for 1 to 4.2 fb⁻¹ of data. These searches are already powerful, setting some of the best limits in the world, and are set to increase their sensitivity with improvements in analysis techniques and through the rapid accumulation of data at the Tevatron. No signal has been observed yet, but new regions and models are continually being investigated, promising many exciting results ahead.

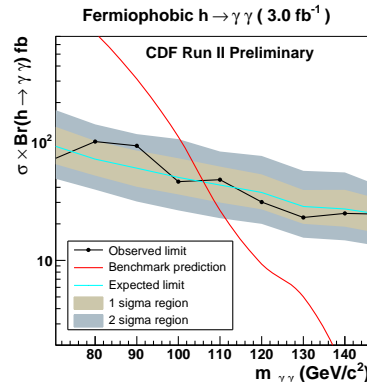


Figure 6: The 95% CL on $\sigma \times BR$ as a function of the Fermiophobic Higgs mass for CDF.

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